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Cover: The number of cave pearls in Gruta de las Canicas, Tabasco, Mexico, has recently been estimated to be in excess of 200 million (Pisarowicz 2001 - *Carbide Flash*). Photo by Robert Stucklen.

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SOLUTE TRANSPORT THROUGH LABORATORY-SCALE KARSTIC AQUIFERS

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Laboratory-scale models of branchwork and of network karstic aquifers were constructed to provide data needed for calibration of numerical models. The distribution and connectedness of the conduits and sinkholes were scaled similarly to those found in nature; however, the porosity of models (2 and 3%) and the recharge rate (80 cm/hr) could not be scaled appropriately. Pulses of 1-M NaCl were injected sequentially at ten locations on both models to determine transport parameters using QTRACER. For all experiments, the Reynolds numbers were <150, the Peclet numbers were >6, and the Froude numbers were ~0. The flow regime was laminar and subcritical and advective processes dominated transport processes. The mean tracer transit times were significantly greater in the network model (29 s and 49 s) than in the branchwork model (17 s and 35 s) for injection locations that were proximal to (<10 cm) and distal from (10-20 cm) the spring. The lag times and times to peak concentration were highly variable and no systematic variation with distance from the spring could be discerned. The results can be used in calibration of numerical models of tracer transport through karstic aquifers.

Numerical models have been developed to predict how groundwater flow and tracer transport occurs through karstic aquifers (Teutsch 1994; Mohrlok & Teutsch 1997; Mohrlok & Sauter 1997; Mohrlok *et al.* 1997; Annabelle & Sudicky 1999; Quinn & Tomasko 2000; Peterson & Wicks 2000). One important step in evaluating numerical models is model calibration in which the results from a modeling effort are compared to results from field or laboratory studies (Anderson & Woessner 1992). The calibration of numerical models has been hindered by a lack of data from field and laboratory experiments in which the flow paths are known. Thus, the goal of this study was to provide data that are needed for calibration of numerical models by conducting well-controlled tracer transport experiments in constructed laboratory-scale models of karstic aquifers.

Palmer (1999) clearly states the pitfalls of building scale models and interpreting the results from scale models. The laboratory model must reflect more than a reduction of the scale of physical parameters (length, conduit size, etc.) and it must maintain similar forces. Palmer (1999) suggests that critical parameters are the Reynolds number and Froude number for modeling flow through open and closed channels. As the experiments conducted in this study are solute transport experiments, the Peclet number is also critical as it compares movement of the solute by advection to that due to diffusion.

Several other studies have relied on construction of laboratory-scale models of aquifers to gain a better understanding of flow and transport processes. Silliman *et al.* (1987), Saiers &

Hornberger (1994), and Saiers *et al.* (1994) used small-scale models of modified sand-packed columns to study contaminant transport through porous media. Toran & Palumbo (1992) and Ibaraki & Sudicky (1995a; 1995b) used small-scale models of fractured media to study colloidal transport and solute transport. The main use of small-scale models of karstic aquifers has been for studies related to the formation of dissolutional features (Ewers 1972; Glew 1977). Recently, Jeannin *et al.* (1999) developed a small-scale model of one reach of cave stream to study dispersion. Our objectives were to develop laboratory-scale models of karstic aquifers, to conduct tracer transport experiments, to clearly document problems encountered, and therefore to provide data that can be used in calibrating numerical models.

CONSTRUCTION OF THE MODELS

Based on measurements on over five hundred cave maps, Palmer (1991) has described five conduit patterns. He found that branchwork conduits represent 57% of the total conduit length and network conduits represent 17% of the total conduit length. The other three types are anastomotic (3%), ramiform (9%), and single conduit (1%) (Palmer 1991). Because hydrogeologic conditions consistent with branchwork and network patterns are predominant in nature, we have chosen to build a model of branchwork and a model of network conduit systems. Both models were created using the same construction method and materials.

Table 1. Porosity and permeability of the cores of fired ceramic clay.

Material	Temperature (°C)	Porosity (%)	Permeability (μ Darcys)
Hawthorn 35 mesh	970	4 \pm 0.15	33.5 \pm 14.5
	1100	10 \pm 0.20	12.6 \pm 0.01
	1300	2 \pm 0.15	6.4 \pm 51.7
20-mesh fireclay	970	12 \pm 0.06	154 \pm 51.7
	1100	8 \pm 0.06	177 \pm 25.5
	1300	2 \pm 0.06	25.2 \pm 0.01
Red Earthenware	970	13 \pm 0.81	637 \pm 85
	1100	3 \pm 0.10	25.2 \pm 0.01
	1300	NA ¹	NA ¹

¹ The samples of red earthenware that were fired at 1300°C flowed (fluxed).

CONSTRUCTION MATERIALS

Because our objective was to document flow characteristics and not dissolution processes, the choice for the modeling material was based on the needs that the material must be easily molded and acquire characteristics of karstic limestones (low matrix permeability and porosity and high secondary permeability). Two choices were plaster of Paris and ceramic clays. Because plaster of Paris dissolves in water, ceramic clays were chosen. Three ceramic clays were available for use: Hawthorn 35 mesh, 20 mesh fireclay, and red earthenware clay. The kiln could be set to three temperatures 970°C, 1100°C, and 1300°C. Three cores (3.8-cm in diameter and 1.0-cm in height) of each material for each temperature were made and fired. After firing and cooling, the porosity and permeability of each core were determined by calculating the change in weight by saturation with water and by using a falling-head permeameter. From these test results (Table 1), the 20-mesh fireclay fired at 970°C was found to provide the best match to the porosity (12%) and permeability (154 μ darcys) for the Burlington Formation of the mid-continent (Hoag 1957). We chose to represent the Burlington Formation because of its widespread distribution throughout the mid-continent and because of its ecological importance to Ozark cavefish (Bergstrom 1997).

FORMING THE MODELS

Using a process similar to lost-wax casting, a 10 cm x 10 cm x 5 cm frame of plywood was constructed for use in making the models (Fig. 1). Into the frame, moist ceramic clay was pressed to a depth of 3 cm. The pattern for the conduits was laid in place using strands of yarn. The yarn was chosen because it was thick enough to support the weight of the wet clay and because it would completely burn when the model was fired in the kiln. This process left conduits where the yarn

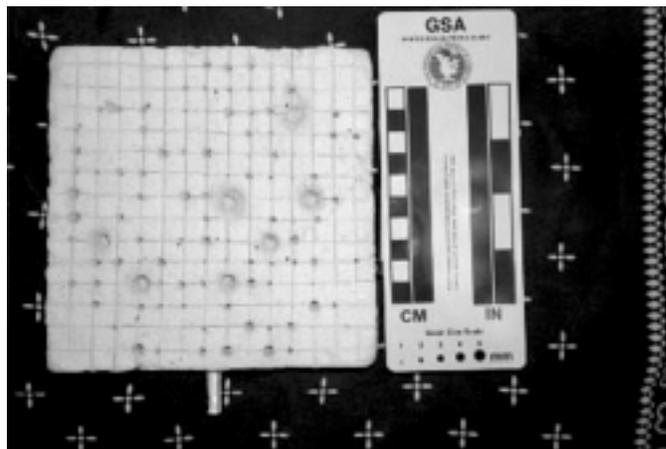


Figure 1. Photograph looking down onto the top of the branchwork model, the sinkholes are visible as is the epikarstic surface (grid pattern).

had been. A 2-cm thick top portion of the moist ceramic clay was gently laid on top of the strands of yarn and lower layer of clay (the base of the model). The seam between the top portion and the base was sealed using finger pressure. Into the top surface of the top of the model were carved sinkholes (described below) and an epikarstic surface (also described below). The completed ceramic models were air dried for several days and then were fired at 970°C, which completely burned the yarn and left conduits. After the models had cooled, all of the outer surfaces, except for the top of the models, were coated with melted wax, which once hardened served as no-flow boundaries. A detailed description of the construction process is available in Florea (1998).

SINKHOLES

Karstic aquifers receive recharge via diffuse flow (slow percolation) through the matrix, relatively rapid recharge through fractures, and more rapid flow through sinkholes and losing streams (White *et al.* 1995). Therefore, the models had to include locations for rapid recharge (sinkholes). The location and diameter of each sinkhole had to be specified. The possible locations for sinkholes were specified by creating a Cartesian grid with 1-cm on center spacing on the surface of the models (Fig. 2). The grid intersections represented all possible sinkhole locations. Representative diameters of six classes of sinkholes were calculated from the depth-distribution function using the coefficient for Missouri karst (Troester *et al.* 1984). The class with the largest diameter sinkholes had the lowest frequency of occurrence. The location of each and every sinkhole was determined by drawing random numbers representing grid locations on the surface of the model. The number of sinkholes of a given class and the distribution of the sinkholes on the surface of the models were the same between the two models (Fig. 2).

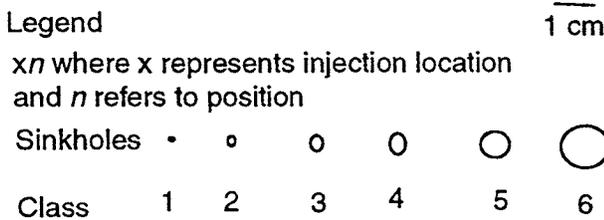
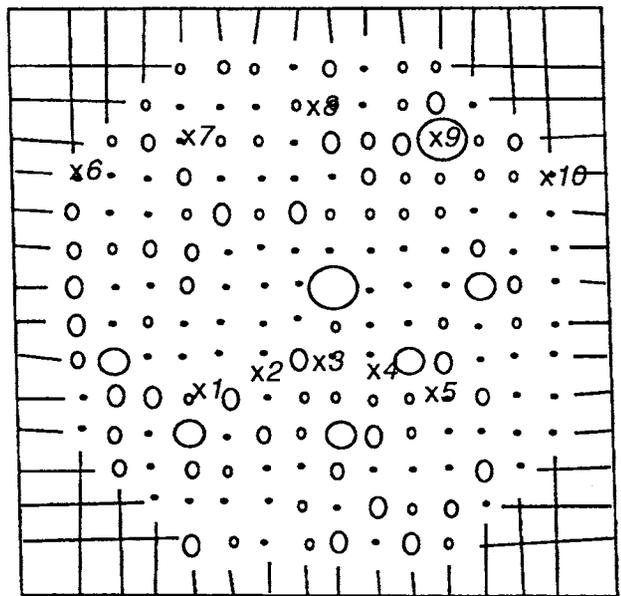


Figure 2. Diagram of a partial grid pattern representing the epikarstic surface, of the injection locations, and of the location and diameter of all sinkholes.

CONDUITS

The number and diameter of the conduits were calculated using the work of Curl (1986), who showed that the number of conduits of a given diameter can be calculated if the fractal dimension is known. In this study, the fractal dimension used was 2.5 (Curl 1986). A conduit segment connects two adjacent grid locations and had a 1-cm length. The diameter of any given segment was calculated using fractal statistics. The resulting distribution of diameters was grouped into five classes. The locations of the segments of a given class were determined by using the distribution of sinkholes on the surface of the models (larger conduits are needed to carry the extra recharge provided by larger sinkholes). In addition, the diameter of the conduits increased in the direction of groundwater flow (Padilla & Pulido-Bosch 1995). Both models were created with the same number of conduit segments of a given class.

The difference between the two models was the conduit morphology (branchwork or network). Branchwork morphologies are dendritic in the distribution of conduits and have only one path from any input location to the spring (Fig. 3a). Network morphologies (mazelike) contain conduits that are highly interconnected. Within network systems, multiple paths exist from any input point to the spring (Fig. 3b). It is noted

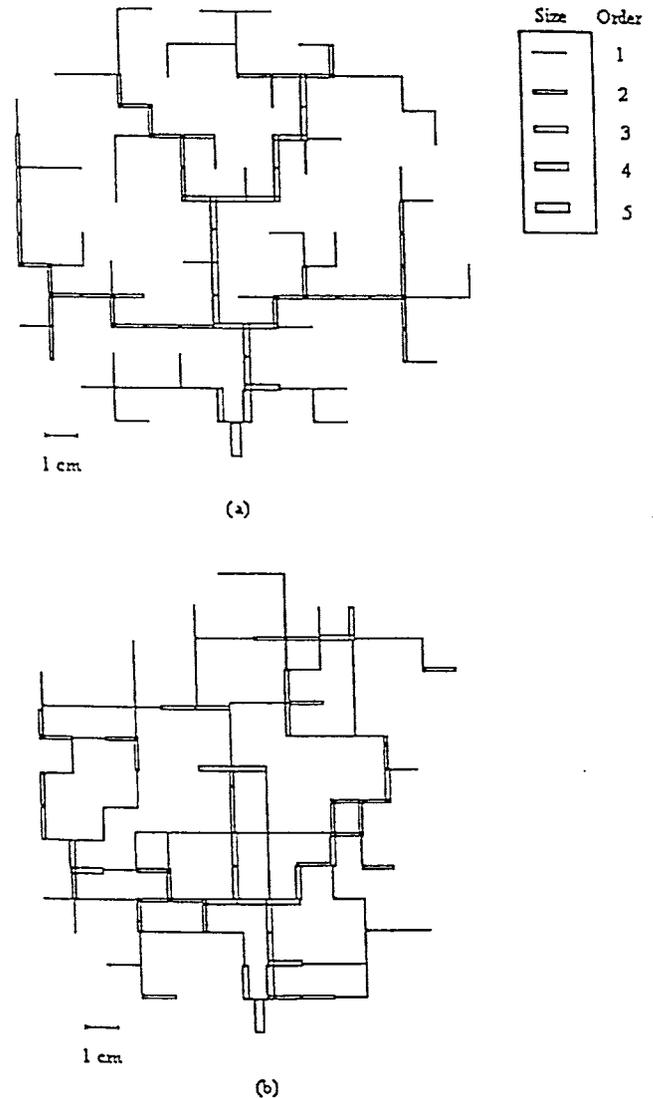


Figure 3. Diagram of the patterns of conduits in the a) branchwork model; b) network model. The sinkholes penetrate vertically downward into the horizontal plane along which the conduits are developed.

that the geometries created within the models are a subset of all possible geometries for each of the morphologies. It is also noted that karst aquifers can exhibit a combination of morphologies (Palmer 1991) that were not considered in this study.

The conduits were made from a worsted 4-ply yarn, chosen because the material burns when fired at 970°C and leaves only an ash residue. One strand of yarn was used to represent a first-class conduit segment with a diameter of 0.10 cm. Two strands of yarn loosely twisted together formed the second-class conduit with a diameter of 0.20 cm (three strands: third-class conduit with diameter 0.30 cm; four strands: fourth-class conduit with diameter 0.40 cm; five strands: fifth-class conduit with diameter 0.50 cm). The yarn was laid upon a foundation of ceramic clay in the required pattern and then the upper part of

Table 2. Average results from the tracer transport experiments using the branchwork model. Each result is the average of three independent experiments.

Model	Lag (s)	Peak (s)	Mean (s)	DL (cm)	Pathlength (cm)	Pe	Re	Fr	Delta (mm)	N	Recovery (%)
location 1	1	14	21	1.3	10	14.0	108.0	0.014	0.14	3	33
location 2	2	11	12	0.8	8	14.0	117.3	0.016	0.11	3	31
location 3	3	11	22	3.5	7	6.3	98.0	0.011	0.15	3	40
location 4	3	10	20	1.8	8	8.7	97.3	0.012	0.14	3	28
location 5	2	12	12	1.0	8	8.3	119.0	0.016	0.11	3	30
location 6	5	15	37	6.2	18	10.7	109.7	0.014	0.17	3	26
location 7	4	16	36	3.6	16	17.0	103.0	0.011	0.17	3	20
location 8	7	18	34	2.7	19	14.3	115.7	0.016	0.15	3	20
location 9	4	17	22	1.2	17	22.0	123.7	0.017	0.14	3	35
location 10	3	15	44	17.0	21	8.0	110.3	0.015	0.18	3	28

the model that incorporated the sinkholes was gently laid on top.

THE EXPERIMENTS AND DATA ANALYSES

CHARACTERIZATION OF THE FLOWPATHS

Because the internal geometry of the models was controlled during construction, the length of each flowpath was known. The lengths in the branchwork model were similar to the shortest paths in the network model (Fig. 4; Tables 2 & 3). Because the number and diameter of all conduit segments along each and every path were known, the theoretical pore volumes of the entire model (9.89 mL for both models) and of each and every path (Fig. 4) were calculated. The actual pore volume of each model was measured by completely saturating the lower portion of the model with water, plugging the spring, and carefully measuring the amount of water needed to completely fill the conduits to the bottom of the sinkholes. Though the pore volumes for the two models should be equal as they contain the same number of conduit segment of the same diameter, the measured pore volume of the network model (12.8 mL ± 0.29 mL) was significantly greater than that of the branchwork model (10.2 mL ± 0.29 mL). Significantly more secondary porosity was created in the network model than in the branchwork model during the firing process. It is conceivable that the interconnectedness of the conduits within the network model allowed separation along a plane of weakness (between the upper and lower portions of the models) during the firing process.

EXPERIMENTAL SETUP

Distilled water was delivered to the top of the model through a recharge system that consisted of 256 pipette tips fed by a bifurcating system of tubes leading from a peristaltic pump (Fig. 5). The average rate of recharge was 2.2 ± 0.6 mL/s. A syringe pump was used to inject a 1-M NaCl tracer onto the model at specified locations (Fig. 2) at 6.5 mL/min. A pulse input (9-s duration that resulted in the addition of 1 mL of solu-

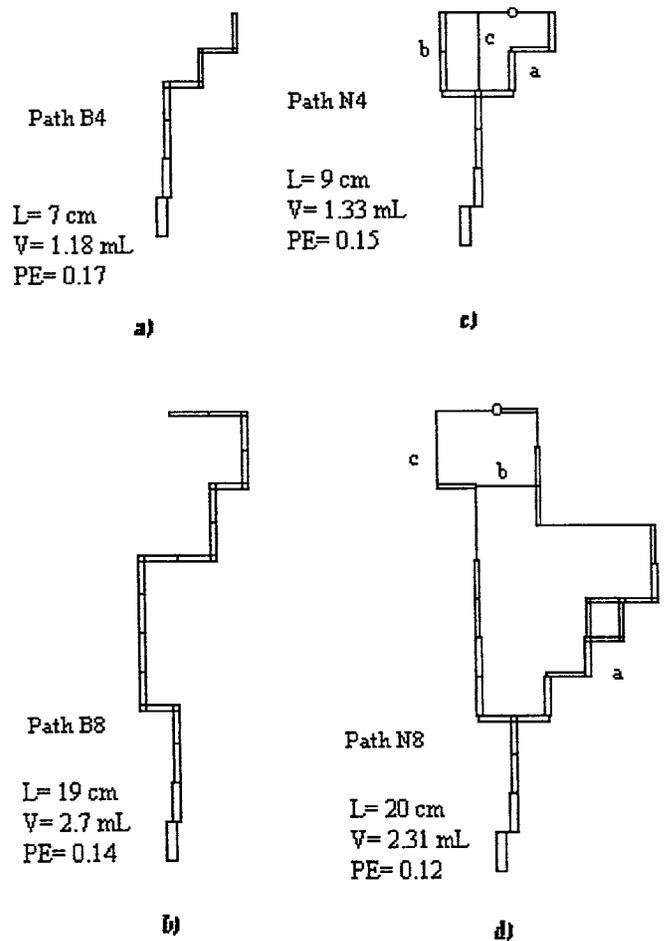


Figure 4. Diagram of selected flowpaths with the length (L) and volume (V) of each selected flowpath shown. The flowpaths are a) path 4 in the branchwork model; b) path 8 in the branchwork model; c) paths 4 a, b, & c in the network model; d) paths 8 a, b, & c in the network model. The length and volume refer to the pathway a in the network model.

Table 3. Average results from the tracer transport experiments using the network model. Each result is the average of N independent experiments.

Model	Lag (s)	Peak (s)	Mean (s)	DL (cm)	Pathlength (cm)	Pe	Re	Fr	Delta (mm)	N	Recovery (%)
location 1	5	12	40	3.0	8	8.7	61.3	0.004	0.20	9	14
location 2	3	10	27	2.3	8	16.0	85.0	0.006	0.17	8	22
location 3	4	12	28	1.2	7	13.0	68.7	0.005	0.17	9	28
location 4	3	12	23	0.9	9	20.3	92.0	0.009	0.15	9	24
location 5	3	12	24	1.1	8	15.0	83.7	0.008	0.15	10	29
location 6	2	27	50	2.5	19	14.7	85.0	0.009	0.19	6	12
location 7	7	27	51	2.8	16	11.0	82.0	0.007	0.20	4	18
location 8	5	21	53	6.2	20	8.0	88.0	0.008	0.19	6	31
location 9	7	19	51	17.0	17	11.3	96.0	0.004	0.18	7	40
location 10	5	15	38	4.4	21	11.7	107.7	0.014	0.16	3	40



Figure 5. Photograph of the experimental apparatus showing the recharge water delivery system and the syringe pump used to introduce the tracer.

tion to the model) was used. The discharge from the model passed through a conductivity cell. The voltage across the conductivity cell was recorded with a strip-chart recorder and the data were digitized. Each conductivity cell was calibrated before and after each set of experiments to provide a conversion from voltage to concentration of tracer. The hydraulic gradient was 0.16 cm per 14.4 cm (1.1%) and was controlled by inserting shims beneath the upgradient end of the model.

EXPERIMENTS

Multiple replicate experiments were performed for each of ten matching input locations on the two models. The five input locations were equally spaced along an arc 3.3 cm from the spring. Another five input locations were equally spaced along an arc 6.8 cm from the spring. The input locations were independent of sinkhole locations, therefore the tracer was not injected directly into a sinkhole. However, at all input locations

it was possible to determine based on sinkhole size or proximity to a sinkhole which sinkhole the tracer entered. As a result, the path that the tracer followed from an input location to the spring was determined and the path length was noted.

Breakthrough curves were plotted against time. For each of the experiments, the time to peak tracer concentration, the mean tracer transit time, the standard deviation of the mean tracer transit time, longitudinal dispersivity, Peclet number, Reynolds number, Froude number, diffusion layer thickness, and percent tracer recovery were calculated using QTRACER (Field 1999). The values of the parameters were averaged for the replicate experiments.

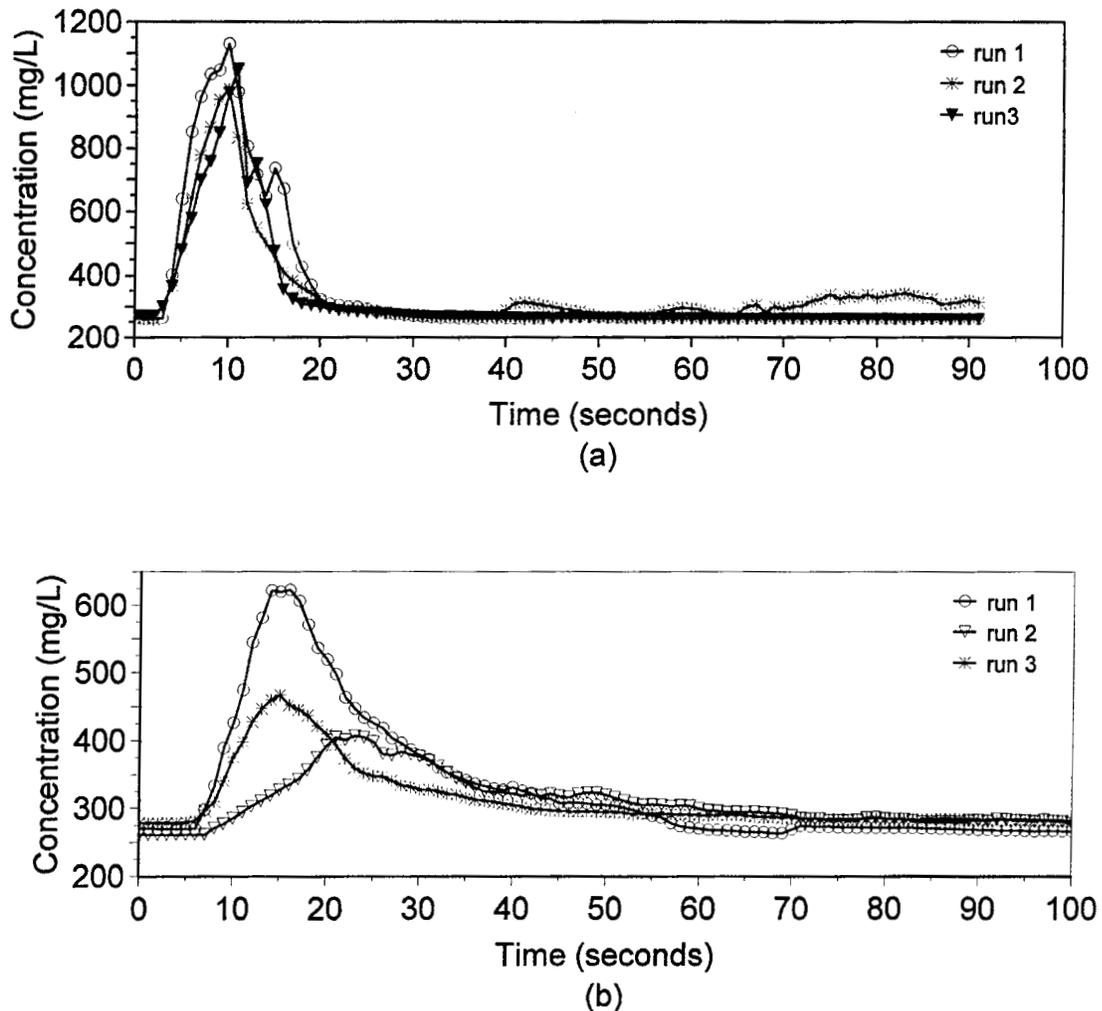
RESULTS

For the tracer transport experiments using the branchwork model, the replicate breakthrough curves (concentration against time) exhibited a reasonable agreement for the injection location that was proximal to the spring and considerable variation for the injection location that was distal from the spring (Fig. 6; Table 2). The times to peak tracer concentration ranged from 10-18 sec. The mean tracer transit times ranged from 12-44 sec. The longitudinal dispersivity varied between 1.0 and 17 cm and represented 12.5-81% of the respective pathlength. The Reynolds and Froude were all within the laminar (<500) and subcritical (<1) flow region. The Peclet numbers (>6) indicated that advection dominated the transport processes. The diffusion layer thickness varied between 0.11 and 0.18 mm and represented 4-8% of the diameter of a class-five conduit.

For the tracer transport experiments using the network model, the replicate breakthrough curves (concentration against time) exhibited a reasonable agreement (Fig. 7; Table 3). The times to peak tracer concentration ranged from 11-26 seconds. The mean tracer transit times ranged from 23-55 seconds. The longitudinal dispersivity varied between 0.9 and 17 cm and represented 10-100% of the respective pathlengths. The Reynolds and Froude were all within the laminar (<500)

Figure 6.

Replicate break-through curves for the branchwork model using injection location 4 and injection location 8.



and subcritical (<1) flow regimes. The Peclet numbers (all >8) indicate that advection dominated the transport processes. The diffusion layer thickness varied between 0.15 and 0.20 mm and represented 6-8% of the diameter of a class-five conduit.

DISCUSSION

Our objectives were to develop laboratory-scale models of karstic aquifers, to conduct tracer transport experiments, to clearly document problems encountered, and most importantly, to provide data that could be used in calibrating numerical models. We have constructed scale models of karstic aquifers in which we controlled the length of the flow paths, the gradient, the recharge rate, the size of the conduits, and the geomorphic pattern of conduit layout.

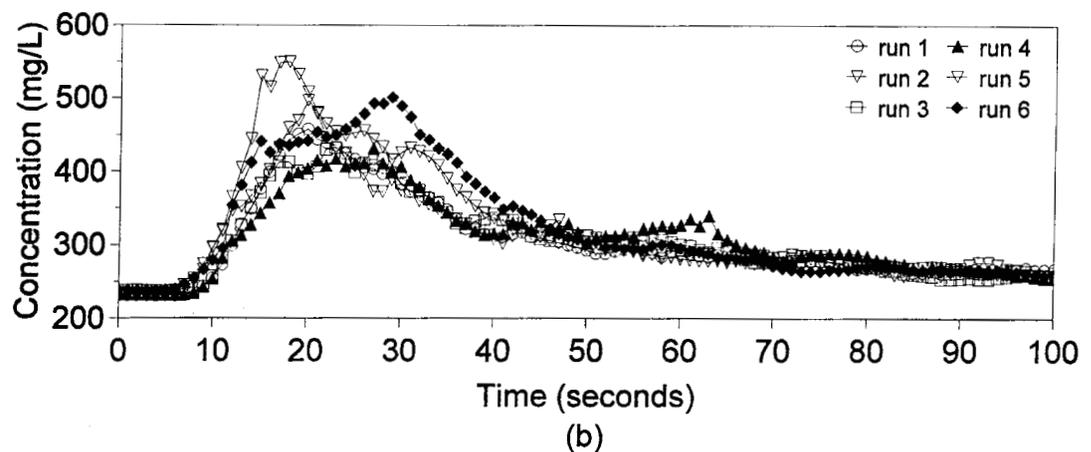
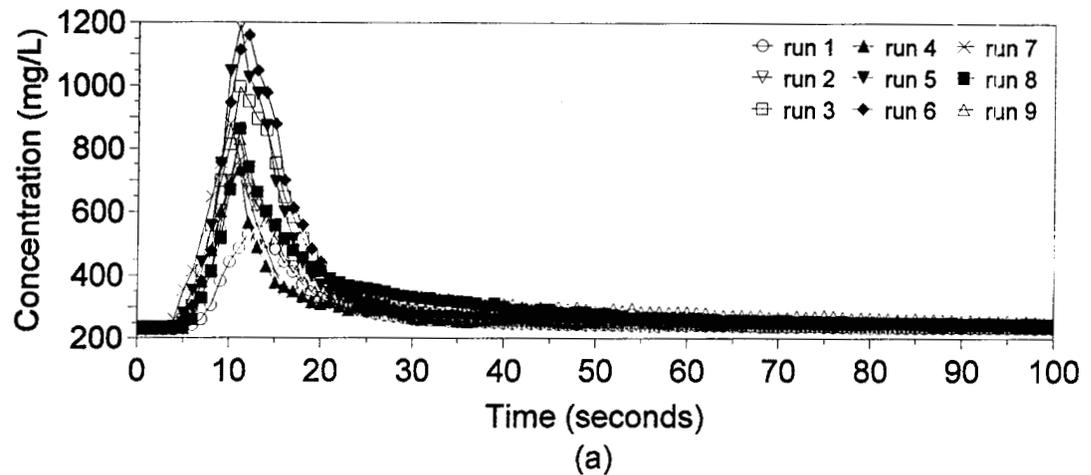
We have calculated the Reynolds number and the Froude number for each and every experiment and have determined that the experiments were conducted under laminar, subcritical flow conditions. These conditions (laminar and subcritical flow) might be expected in karstic aquifers that have a low groundwater velocity, such as the Salem Plateau or the Floridan aquifer at locations away from the discharge points,

the springs. These experiments are not applicable to karstic basins in which the water table intersects conduits, such as the Springfield Plateau. The models of karstic aquifers created in this study provided a means to conduct tracer transport experiments and generate data that are sufficient for validation of numerical models.

There are potential problems that require description and discussion. These are the potential for density-driven flow, the rate of recharge relative to the surface area of the model and the ratio of the diameter of the largest conduit to the surface area. Due to the difference in density of the recharging water ($\rho = 1.00$) and the tracer solution ($\rho = 1.04$), density-driven flow could have occurred in the models. Tracer transport experiments were also conducted using at 0.1 M ($\rho = 1.003$) and 1.0 M NaCl to determine density effects (same injection rate, same injection location). Results (Florea 1998) were virtually identical (other than amplitude), thus effects from density-driven flow appear to be minimal. Another problem was the very high rate of recharge (2.2 mL/s over 100-cm² or 80 cm/hr) that was used. Although the rate of recharge was very high, it was reproducible (Tables 2 & 3). Finally, the volume of the conduits relative to the volume of the model (the porosity) was

Figure 7.

Replicate breakthrough curves for the network model using injection location 4 and injection location 8.



2.6% and 2.0% for the network and branchwork models, respectively. The porosity of the models was lower than the 12% porosity of Burlington Limestone (Hoag 1957), which we had chosen as typical cavernous limestone.

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A SIMPLE MAP INDEX OF KARSTIFICATION AND ITS RELATIONSHIP TO SINKHOLE AND CAVE DISTRIBUTION IN TENNESSEE

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We here introduce a readily determined index of surface karstification, termed "sinkhole" index, based on the mean spacing of closed contours in a given area. The index shows a high correlation with total sinkhole area and a moderate correlation with total volume. The index was measured in 5056 blocks with dimensions of 2.5' of latitude by 2.5' of longitude, covering much of Tennessee. A new map showing the distribution of this index in the state is similar to one previously published karst map of Tennessee, but shows the variation of karstification in a more detailed manner. The sinkhole index was also used to compare the distribution of sinkholes and caves in Tennessee, using cave data compiled by the Tennessee Cave Survey. Maps of the sinkhole index and the number and total length of caves in each 2.5' x 2.5' block show strong regional similarities. However, there are dramatic exceptions. In addition, using blocks as the basic unit of analysis, the correlation coefficients between the sinkhole index and the two measures of cave abundance are low, generally explaining less than 10% of the variance. Thus, although similar geologic conditions appear to favor both sinkhole development and cave formation, the actual processes involved in the development of these two types of features seem to be only weakly related.

Sinkholes are the most common surface feature of karstification that can be recognized on topographic maps, and their abundance and size are indicators of the degree to which the local bedrock has undergone solution. Below we use an index of sinkhole abundance to construct a map showing the variation in karstification across Tennessee. We also address the relationship between sinkhole and cave distribution by relating our sinkhole index to cave-location data from the Tennessee Cave Survey.

PREVIOUS WORK

Sinkholes are the diagnostic karst landform (Cvijic 1893; Ford & Williams 1989), and thus the abundance of closed depressions provides an important measure of karstification. Several measures of sinkhole abundance have been used (White 1988). A common one is sinkhole density, defined as the total number of sinkholes divided by the total area studied. Another is the sinkhole area ratio, which is the ratio of the total sinkhole area to the total area studied. Of these, density has been more commonly used, as counting sinkholes is much faster than measuring their areas. White and White (1979) measured sinkhole densities in 62 drainage basins in the Appalachians, including a number in Tennessee. Kemmerly (1982) measured sinkhole densities on 1-km grids in 42 quadrangles in the Western Highland Rim and Pennyroyal plateau

of south-central Kentucky and northcentral Tennessee, counting more than 25,000 sinkholes.

Miller (1977) has published a karst hazards map of Tennessee showing two levels of karstification: "karst areas," based mainly on the observed association between bedrock geology and karst (see below), and "areas with a high density of karst features," based on examination of topographic maps and ground observations (Miller, pers. comm. 2000).

The relationship between sinkhole and cave development is an important question in karst geomorphology. One effort to investigate this relationship was made by Ford (1964), who studied sinkholes and caves on the Mendip plateau, southern England. He found that 80% of the sinkholes lie in dry valleys with low gradients. Mapping of the caves in the area showed that they did not underlie the dry valleys, and collapses in them did not correspond with surface depressions. Another effort was made by Palmer and Palmer (1975), who studied sinkholes overlying Blue Spring Cave in southern Indiana. Although deeper sinkholes are preferentially located over or close to cave passages, maps of sinkhole density do not closely correspond with cave passages, but show only a general relationship to the known caves. Jennings (1985) infers that this finding suggests some mutual interdependence of sinkhole and cave development but with only a small proportion of the sinkholes being directly connected with underground passages. Based on these studies, the relationship between cave and sink-



Figure 1. Physiographic provinces and counties of Tennessee. Highlighted/labeled counties and cities are those mentioned by Miller (1977), and are discussed in text.

hole development seems to be a weak one.

METHODS

PHYSIOGRAPHY AND GEOLOGY OF THE STUDY AREA

Davies and LeGrand (1972) have summarized the karst topography of the Appalachian Highlands and the Interior Low Plateaus, and Miller (1977) has summarized it for the State of Tennessee, including its relation to stratigraphy. Miller (1977) notes that karst is most extensively developed in the Central Basin, Eastern and Western Highland Rim, and Valley and Ridge physiographic provinces (Fig. 1). In the Central Basin, karst development is especially associated with Ordovician Ridley Limestone and Lebanon Limestone outcrops. On the Highland Rim two areas show the best developed karst. The first is in the northern part of the Western Highland Rim, in northern Montgomery and Robertson Counties (Fig. 1). This area represents a southern extension of the Pennyroyal plateau of Kentucky, where karst is best developed on the Mississippian St. Louis Limestone and the Ste. Genevieve Limestone. The second area is the eastern part of the Eastern Highland Rim, adjacent to and including the lower slopes of the Cumberland Plateau escarpment, chiefly involving the Mississippian St. Louis Limestone and the Monteagle Limestone (equivalent to the Ste. Genevieve Limestone). In the Valley and Ridge province of east Tennessee, the Ordovician Knox Group, some formations of the Ordovician Chickamauga Group (e.g., the Holston Formation), and the Cambrian Honaker Dolomite support the best-developed karst. Specific areas with highly developed karst include the Powell River Valley (principally Claiborne, Campbell, and Union Counties), the lower Holston River Valley (Knox and Jefferson Counties), the Ft. Loudon Lake area (Knox, Loudon, and Blount Counties), and the upper Holston River Valley in the area of Boone Lake.

Quaternary deposits in the karst areas range in thickness from nearly zero to several tens of meters. They consist largely of clay-rich residuum derived from insoluble materials left behind by the dissolution of the limestone units or left from overlying clastic units. Also present are colluvium and, in the western part of the study area, thin loess deposits.

Measures of surface karstification, at least those that can be measured from 1:24,000-scale maps, obviously involve the extent of closed depressions. The total area of closed depressions in a given study area would be a good index, but the time required would be prohibitive, and the available digital elevation models lack the resolution to allow this task to be done by computer. An alternative approach is to count closed depressions, a method used by many researchers. Although somewhat faster than area measurement, this technique is also just too time consuming for evaluating an area covering most of a state, and also encounters difficulties as a measure of karstification where sinkhole size varies greatly from one area to another.

We sought a rapid sampling technique that did not require sinkhole area measurements or actual sinkhole enumeration, and, in particular, a method that would reflect size as well as number of sinkholes. Also desirable was a method requiring as little interpretation by the operator as possible. We devised the following approach. Our unit of study was a block 2.5' of latitude by 2.5' of longitude (area of about 17.4 km²), or one ninth of the standard 7.5' by 7.5' topographic quadrangle. Over each 2.5' by 2.5' block, we placed a transparent grid with 12 horizontal lines and counted the total number of closed (hachured) contour lines crossed by the grid lines. Scanning the lines required no more than a minute or so on maps with no or very few sinkholes, up to 20 minutes on maps with hundreds of sinkholes. For a sinkhole index, we then divided the total length of the grid lines (45.36 km) by the total number of hachured contour lines crossed, thus giving the mean spacing between closed contour lines, a closer spacing indicating a greater degree of karst development (note that by defining it in this manner, the index is relatively independent of either the number or total length of grid lines.) We did this for 5056 blocks covering all but about the western one-fifth of Tennessee (Fig. 2).

Counts were made by two geomorphology classes taught by Mills in 1998 and 2000. Quadrangles were assigned alphabetically rather than by area in order to minimize the effects of bias. The reliability of all operators was checked by having some maps counted by multiple operators and by means of random checks by Mills. Data of unreliable operators were

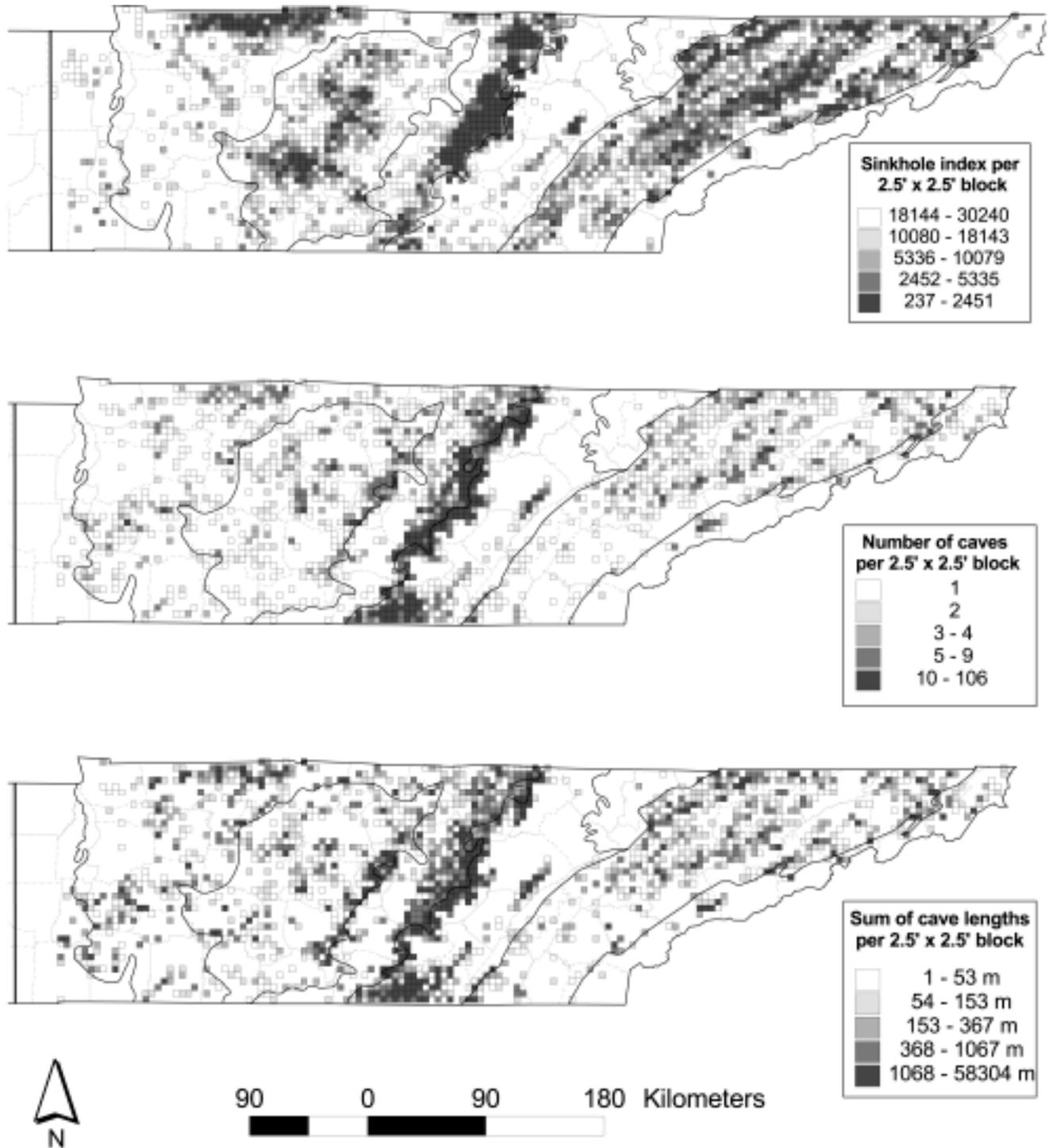


Figure 2. Map showing sinkhole index, number of caves, and sum of cave lengths for each 2.5' x 2.5' block. Note: a lower sinkhole index indicates greater karstification, as lower values mean closer spacing of closed contour lines. Regions with no blocks represent "zero" values, i.e. no closed contours measured/observed, or no caves recorded. Heavy vertical line to the extreme left delimits the western extent of the study area. Heavy irregular lines show physiographic province boundaries; provinces are identified in figure 1.

rejected. The total labor represented in making the counts was about 250 hours.

The block counts were entered into a plain-text database that was manipulated by custom FORTRAN code to produce

Figure 3.

Enlarged map showing sinkhole index and number of caves in each 2.5' x 2.5' block for portions of the Western Highland Rim and Central Basin physiographic provinces. CLARK = Clarksville, CMB = Cumberland River, DK = Duck River, MURF = Murfreesboro. Physiographic provinces are identified in figure 1.

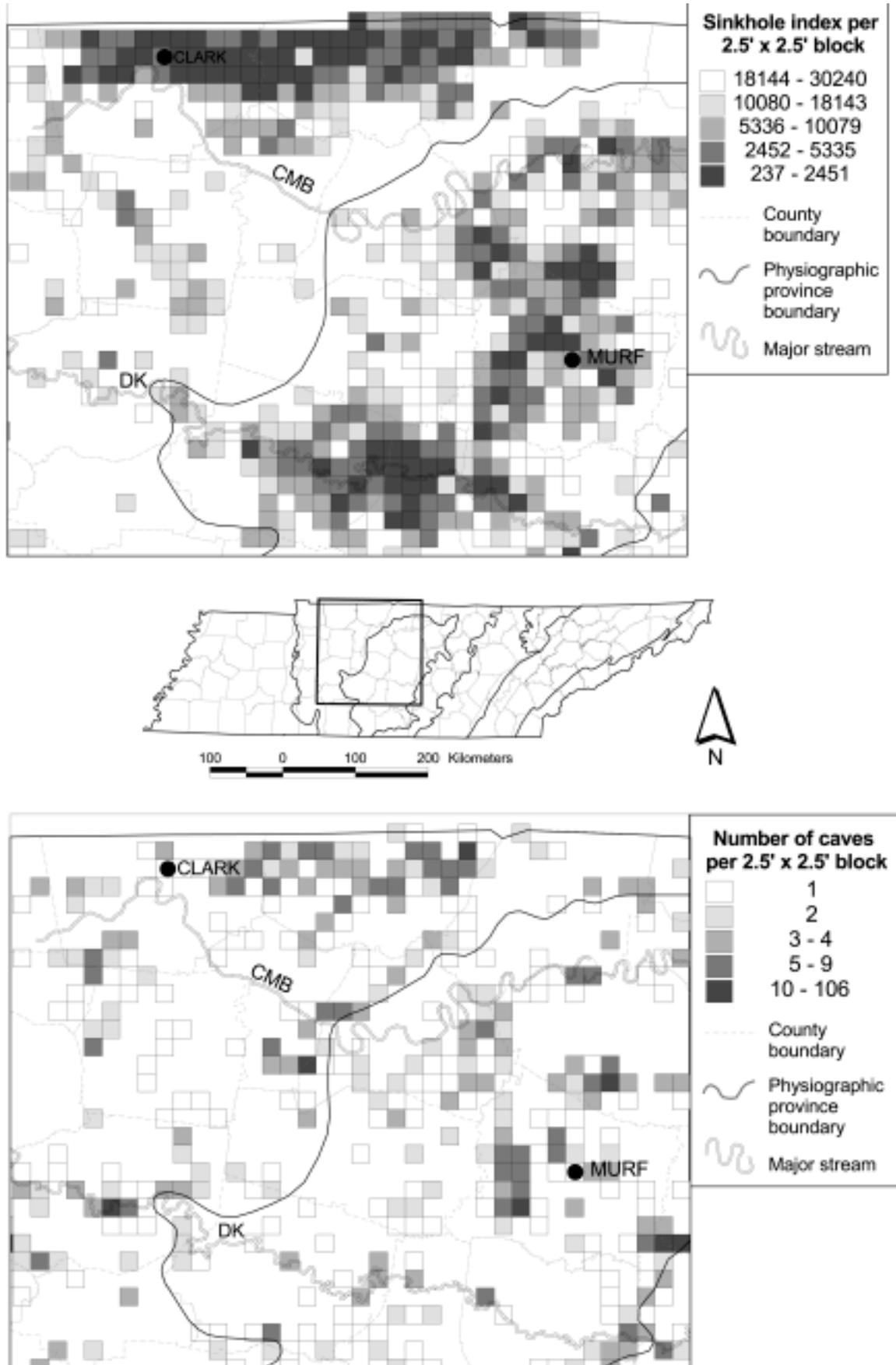


Table 1. Mean values by physiographic province.

Physiographic province	N	Karst index = mean spacing of closed contours (m)	Mean number of caves	Mean sum of cave lengths (m)
Unaka Mts	362	42,293 (41,241-43,346)	0.44 (0.29-0.59)	117.5 (34.4-200.5)
Valley & Ridge	1134	17,949 (16,915-18,983)	1.13 (0.97-1.29)	182.0 (142.4-221.7)
Cumberland Mts	136	43,631 (42,432-44,831)	0.04 (0.00-0.07)	5.8 (0.0-13.1)
Cumberland Plateau	655	38,998 (37,930-40,066)	3.77 (3.08-4.46)	912.7 (538.0-1187.4)
E Highland Rim	431	20,398 (18,568-22,228)	4.29 (3.53-5.06)	912.5 (559.3-1265.7)
Central Basin	863	28,836 (27,260-30,035)	0.85 (0.73-0.97)	213.3 (148.0-278.5)
W Highland Rim	1047	36,653 (35,397-37,909)	0.61 (0.52-0.69)	150.9 (109.3-192.5)
All provinces	4628	30,077 (29,370-30,783)	1.54 (1.40-1.68)	342.0 (286.9-397.1)

The 95% confidence interval is given in parentheses.

Table 2. Correlation coefficients (r values).

Physiographic province	N	Karst index vs. number of caves	Karst index vs. length of caves	Number of caves vs. length of caves
Unaka Mts	362	0.394	0.251	0.439
Valley & Ridge	1134	0.235	0.153	0.623
Cumberland Mts	136	0.298	0.296	0.866
Cumberland Plateau	655	0.409	0.267	0.572
E Highland Rim	431	0.286	0.106	0.364
Central Basin	863	0.105	0.005	0.531
W Highland Rim	1047	0.268	0.178	0.511
All provinces	4628	0.204	0.100	0.515

the sinkhole index, including normalization to a common contour interval of 20-ft, that being the most common interval on Tennessee maps. Thus, counts done on a map with 10-ft intervals were halved, and counts done on a map with 40-ft intervals were doubled. (One possible inadequacy with such normalization is addressed below.)

To compare the distribution of sinkholes and caves, we used data provided by the Tennessee Cave Survey (TCS), specifically the location of the entrance and the length of each recorded cave in Tennessee. (Only one entrance was used for caves with multiple entrances.)

Microsoft Access was used to parse the TCS cave data to produce a data set usable within ArcView. The point locations of the cave entrances and the corresponding cave lengths were transformed into indices based on the same 2.5' x 2.5' blocks as the sinkhole index, by means of spatial queries within ArcView. Because it was not possible to constrain the spatial orientation of the caves, the entire length of any given cave was attributed to the same block as its entrance. All analyses in ArcView, including these queries, were based on a shapefile comprised of 5056 rectangular polygons.

Although intuitively obvious that the index is related to the abundance of sinkholes, we sought to define more precisely just what attributes of sinkholes the index reflects. To do this

we generated 20 synthetic maps, representing sinkholes as inverted cones of varying area, depth, and density. (The advantage of conic sinkholes is that area and volume can be determined exactly.) We then overlaid grids on these maps and measured the sinkhole index of each. We then correlated the index with the total area and total volume of sinkholes on each map. The log-log correlation coefficient between the index and total sinkhole area was -0.974 ($R^2 = 0.949$), whereas that between the index and total volume was -0.803 ($R^2 = 0.645$). Thus, the index seems to be an excellent indicator of sinkhole area, and is a fairly accurate indicator of sinkhole volume.

RESULTS AND DISCUSSION

On a small scale, the distribution of the sinkhole index in Tennessee (Fig. 2) generally agrees with Miller's (1977) karst map. However, whereas Miller's map delineates only two levels of karstification, the quantitative approach used here provides more detail on the degree of karstification. Figures 3 and 4 show enlarged views of selected areas of figure 2, focusing on the Western Highland Rim/Central Basin and the Eastern Highland Rim/Cumberland Plateau, respectively (Figures 3 and 4 show only the plot of cave numbers. However, as figure 2 shows, plots of sum of cave lengths and cave numbers are

Figure 4.

Enlarged map showing sinkhole index and number of caves in each 2.5' x 2.5' block for portions of the Eastern Highland Rim and Cumberland Plateau physiographic provinces. CNY = Caney Fork River, CK = Cookeville, MCMN = McMinnville, OBY = Obey River, SEQ = Sequatchie River. Physiographic provinces are identified in figure 1.

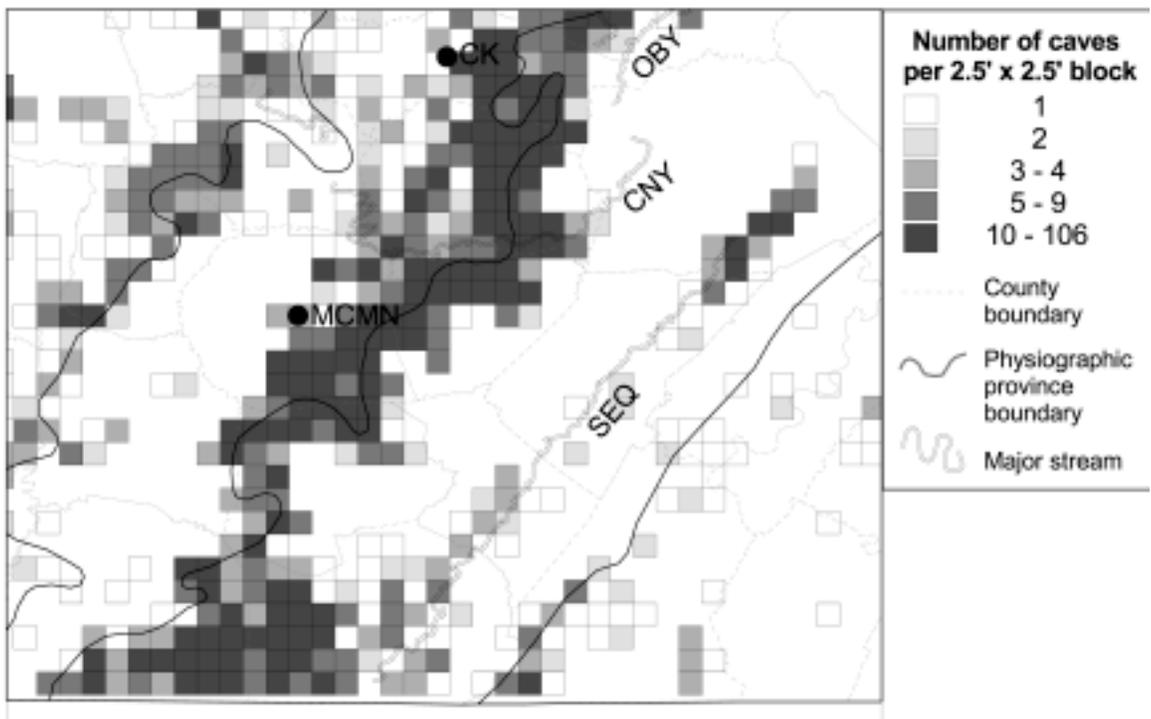
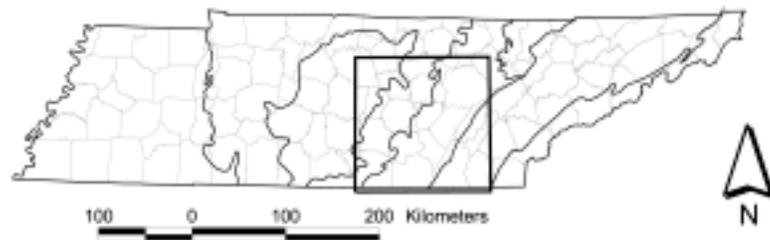
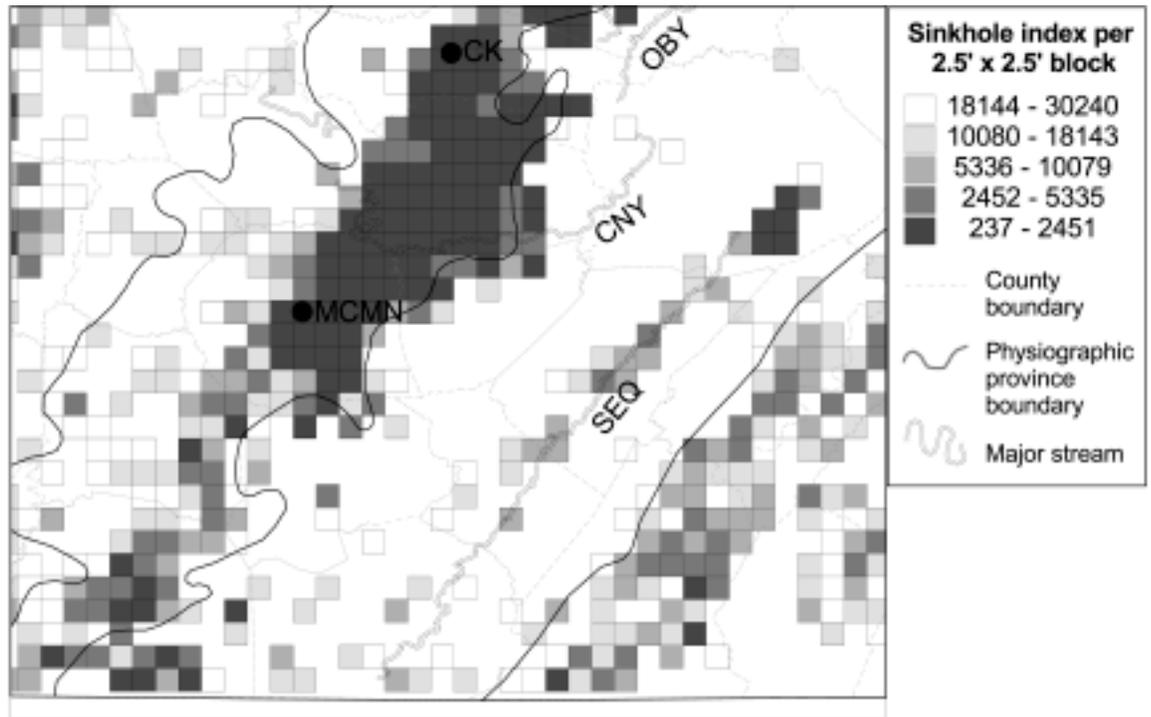
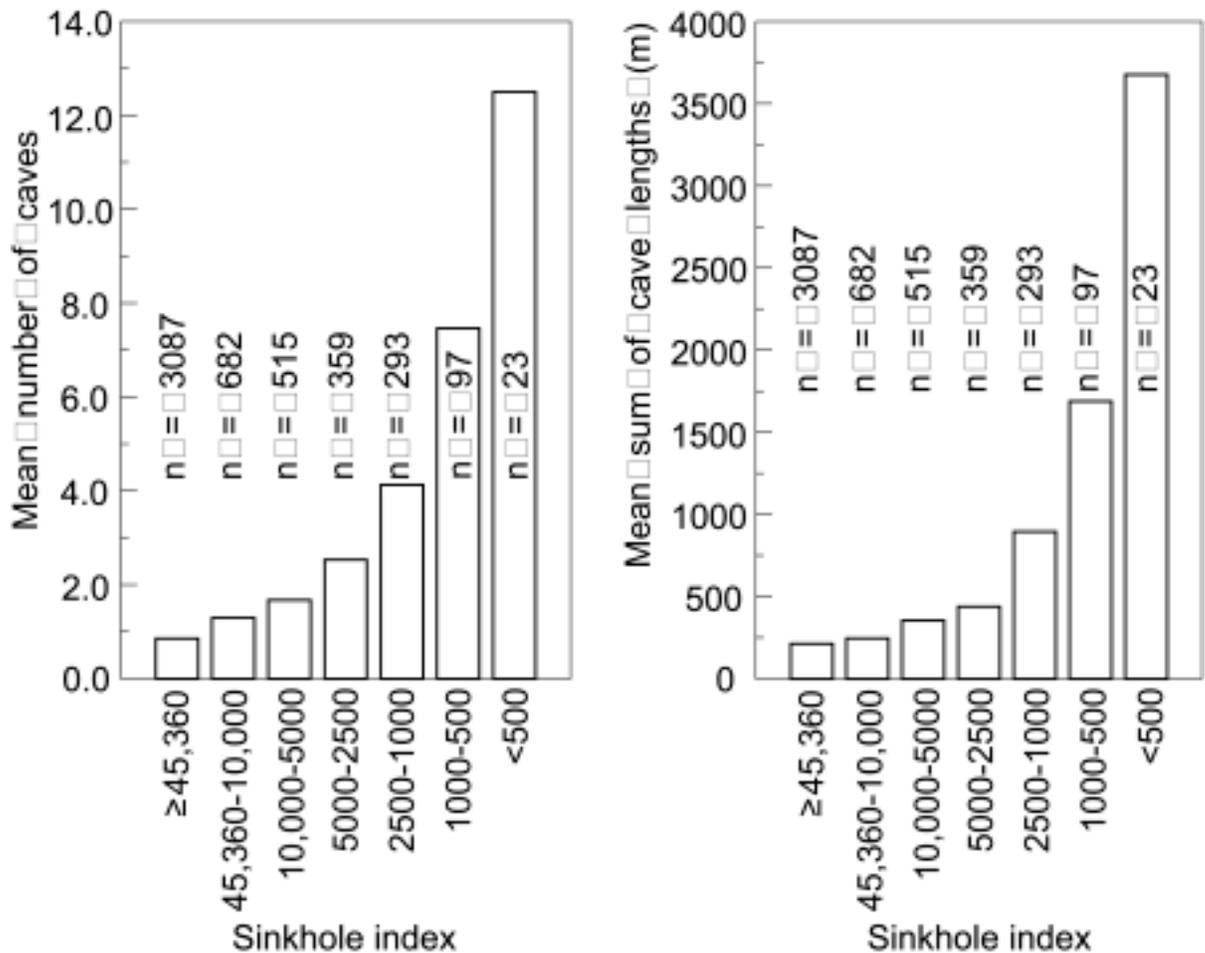


Figure 5.

Histograms showing variation in mean number of caves per block and mean sum of cave lengths per block as a function of sinkhole index. The n values are the number of blocks in each interval.



very similar). Table 1 shows the mean sinkhole index, mean number of caves, and mean sum of cave lengths for the major physiographic provinces of Tennessee, excluding the westernmost ones. Note that the physiographic boundaries shown in the figures have been simplified for presentation; more detailed boundaries were used for calculations.

Karstification generally is closely associated with areas underlain by carbonate bedrock. The sinkhole distribution map of figure 2 shows that the Highland Rim, Central Basin, and Valley and Ridge physiographic provinces, which are largely characterized by carbonate bedrock, all show extensive sinkhole development. But sinkholes are sparse in many carbonate areas, especially in the Central Basin and Highland Rim provinces. Extensive sinkhole development in the Central Basin is restricted to two areas, one centered around Murfreesboro, the other following along the course of the Duck River to the south (Fig. 3). This may be bedrock related, as the Ridley Limestone and Lebanon Limestone both crop out in these areas, and the intensity of sinkhole development diminishes where younger units are present. In the Western Highland Rim, the most intensive sinkhole development is limited to a small region in the northern part of the state, yet the entire region is predominantly limestone. In the Eastern

Highland Rim, the intensity of sinkhole development ends fairly abruptly along a line trending southwest-northeast through Cookeville and McMinnville, with the sinkhole concentration lying to the east of this line (Fig. 4). Bedrock also seems to play a role in both of these cases, as the Eastern Highland Rim trend and the Western Highland Rim zone correspond to the stratigraphic contact between the Warsaw Formation and the overlying St. Louis Limestone (both Mississippian), with the sinkholes occurring mostly in the St. Louis.

A possible problem with the normalization technique used here to correct for map contour interval is that the number of sinkholes has been shown to increase exponentially with decrease in depth (Troester *et al.* 1984). In other words, a map with a 10-ft contour interval might show not merely twice as many sinkholes as a map with a 20-ft interval, but many times more, with a corresponding effect on the sinkhole index. However, at least in the present setting, this problem appears to be minor. First, 80% of the Tennessee maps have 20-ft contour intervals, 12.6% have 10-ft intervals, and most of the remainder have 40-ft intervals. The latter occur mainly in the Unaka Mountains, where karst areas are sparse, so the problem chiefly concerns the 20-ft vs. the 10-ft maps. The large difference between these two maps that might be expected from con-

sideration of Troester *et al.* (1984) simply does not occur. The mean sinkhole index for 10-ft maps is 23,294, only 26.1% different from the 31,522 value for 20-ft maps. Further, a large part of this difference appears to stem from the location of most 10-ft maps in karst areas (northernmost Western Highland Rim, central Central Basin, and southwestern part of the Eastern Highland Rim), whereas 20-ft maps are located in many non-karst as well as karst areas.

Concerning the relationship between sinkholes and caves, a comparison of the distribution of the sinkhole index, number of caves, and sum of cave lengths (Fig. 2) clearly shows a regional relationship between sinkholes and caves. However, there are also some pronounced differences. For example, note that the southern cluster of blocks in the Central Basin with high sinkhole densities shows little corresponding concentration of caves (Fig. 3). Perhaps the low relief in this province precludes access to many undiscovered caves that are present. Another discrepancy occurs in the southwestern part of the Cumberland Plateau, which shows a high cave density, yet a low sinkhole density (Fig. 4). An explanation probably involves the high degree of fluvial dissection in this part of the Plateau; sinkholes occur mainly only along the floors of narrow valleys. The walls of these valleys, however, provide access to many caves that have developed below the sandstone caprocks of the Plateau. Also note the concentration of sinkholes and caves near the boundary between the Eastern Highland Rim and the Cumberland Plateau. The sinkhole concentration is mainly on the Rim, but the cave concentration is somewhat farther to the southeast. This difference probably reflects the fact that many of the cave entrances occur along the escarpment where sinkholes are relatively few.

Figure 5 shows that as sinkhole index decreases (i.e., the density of closed contours increases), the number and length of caves rises, particularly for the higher ranges of sinkhole index values. However, on a block-by-block basis, the relationship is somewhat weaker. Table 2 shows the correlation coefficients between the sinkhole index and cave number and length for the major physiographic provinces. As can be seen, the correlation coefficients are low, although significant at the $p \leq 0.05$ level in most cases. The maximum percentage of variance explained is less than 17%, and less than 9% in most cases. The correlation between the sinkhole index and the mean sum of cave length is somewhat weaker than that between the index and the number of caves. This result may be partly due to the fact that the greater part of the cave length attributed to a given block may actually lie in a block different from that in which the cave entrance is located.

CONCLUSIONS

The general correspondence between the maps of the sinkhole index and the previously compiled karst map by Miller (1977) supports the validity of this index. The present map based on a more quantitative method, shows the variation in karstification in more detail than does Miller's map. In addi-

tion, experiments with synthetic sinkhole maps suggest that the index accurately reflects total sinkhole area.

The visual correspondence between the sinkhole index and the abundance of caves indicated by the number and total length of caves in each block clearly indicates that conditions that favor sinkhole formation also favor cave formation. However, low correlation coefficients between the sinkhole index and number and length of caves show that this correspondence does not apply in a block-by-block manner. Thus, we must conclude that whereas similar conditions appear to favor both sinkhole development and cave formation, different and only weakly related processes are involved in the formation of the two types of karst features. This conclusion is similar to that of previous researchers.

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DISCUSSION: “POST-SPELEOGENETIC EROSION AND ITS EFFECT ON CAVES IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND WEST TEXAS”

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DuChene & Martinez (2000) consider the erosional dissection of the Guadalupe Mountains as it affects the distribution and dimensions of known caves in each of three physiographically defined segments. They conclude that “long [defined as >8 km] cave systems probably once existed throughout the Guadalupe Mountains, but west of Rattlesnake Canyon erosion has mostly destroyed them...” Their paper contributes valuable data, but does not address an important question: is the distribution and size of known caves primarily controlled by erosional dissection (which could lead to the inference above), or by prior speleogenetic factors?

They state: “The longest known caves are in the eastern segment of the mountains where erosion has not cut deeply enough to expose cave-bearing strata...” This is true, but much more can be said about cause and effect relationships of Guadalupe cave distribution, which probably was not originally uniform through the mountains.

If one considers DuChene and Martinez’s three segments in terms of verified cave distribution as well as physiography, their western and eastern segments can each be further subdivided. The new far western segment, from about McKittrick Canyon west (mostly coinciding with Guadalupe Mountains National Park) has about an order of magnitude fewer and smaller known caves than the eastern (Lincoln National Forest) half of their original western segment. The original eastern segment can be split east of Carlsbad Cavern. The short western sub-part contains Lechuguilla Cave and Carlsbad Cavern, each of which has at least an order of magnitude more passage length and volume than any other known Guadalupe cave. (In the area studied, these two are the only caves presently known that are “long” as defined by the authors.) The easternmost sub-segment has relatively few and short known caves.

For the original western segment, DuChene & Martinez say “If surface erosion and mass wasting followed the joint systems that controlled speleogenesis, then the largest parts of many of these caves have been destroyed.” However, I have seen little demonstrable correlation between passage locations and surface geography in the Guadalupes. Surface canyons do not routinely align with cave passages. Over Lechuguilla and Carlsbad, the two least-dissected major Guadalupe caves, surface drainage patterns do not mirror the underlying cave voids (except for Bat Cave Draw).

DuChene & Martinez do not quantify the differences in erosional volume removal between the Guadalupe Mountains National Park and Lincoln National Forest halves of their western segment (~32% for the entire segment), but greater erosion alone does not appear to be sufficient to account for the roughly order-of-magnitude difference in cave length and size between these two sub-areas. Some of the discrepancy may reflect less exploration in the Park, but my personal observation does suggest sparser distribution of entrances and solution features there.

For the far eastern Guadalupes from Carlsbad Cavern northeast, long caves may remain undissected, but we have no direct evidence of that.

Speleogenesis in the Guadalupes has been episodic (Palmer & Palmer 2000); even within Carlsbad and Lechuguilla, voids and levels have limited interconnection and erratic distribution, and at least one interval of raft deposition intervened between episodes of dissolution. The watershed has also enlarged with uplift. It follows that the intensity of speleogenesis has varied from west to east as uplift proceeded. It is, thus, unlikely that cave abundance and size range were originally similar throughout the mountains. The numbers and sizes of caves we see now may owe at least as much to the configuration of hidden sulfuric acid sources, and to changes in hydrologic recharge, as they do to variations in exposure and destruction by erosion.

As I have mentioned (Davis 2000), the occurrence of subterranean rillenkarren in Carlsbad, Lechuguilla, and nearby Mudgetts Caves (and not in others to the west or northeast) suggests a higher paleotemperature gradient in the caves of that block, which in turn implies more intense speleogenesis (since the reactions involved in sulfuric-acid speleogenesis are exothermic). These caves may well be exceptional, and systems on that scale may not have been widespread in the overall range of Guadalupe speleogenesis. The caves destroyed by erosion in the western Guadalupes were not necessarily much larger than those surviving there at present.

REPLY: “POST-SPELEOGENETIC EROSION AND ITS EFFECT ON CAVES IN THE GUADALUPE MOUNTAINS, NEW MEXICO AND TEXAS”

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In his discussion of our paper on erosion, Davis (2001) presents thought-provoking comments on erosion and speleogenesis in the Guadalupe Mountains (DuChene & Martinez 2000). We respond to Davis' comments on the impact of erosion on caves, and address his remarks on speleogenetic history. We point out, however, that speleogenesis is beyond the scope of our original paper.

We agree that erosion is not the sole control on cave distribution; tectonic events, climatic changes, dynamics of the groundwater system, and exhumation of the Capitan Reef Complex are other important factors.

Davis observes that the three segments we selected for our study of erosion can be subdivided based on the distribution of caves. This is true, but is not a valid approach for a study of erosion. We divided the mountains into three segments based on topographic slope, which is a reflection of the structural geology. Our west and east segments slope east at 1.2° and 1.1°, respectively, and are developed on an east-dipping regional homocline. This homocline is interrupted by the north-northwest trending Huapache Monocline, which crosses the Guadalupes between Double and Rattlesnake Canyons. This segment has a 2.2° eastward slope reflecting the steeper dip of the monocline. Our divisions are, therefore, based on topographic slope and structural dip, which *contribute* to erosion, rather than caves, which are a *product* of erosion.

In his discussion of our western segment, Davis states, “...I have seen little demonstrable correlation between passage locations and surface geography in the Guadalupe Mountains. Surface canyons do not routinely align with cave passages.”

An examination of joint patterns in the Guadalupes shows two prominent trends: one parallel to the Capitan Shelf Margin and the other approximately perpendicular to it (King 1948; Jagnow 1979). Many of the largest and most extensive passages in Carlsbad Cavern and Lechuguilla Cave parallel the Shelf margin. We assume that many cave passages in the western segment were similar in orientation to Carlsbad and Lechuguilla. Jagnow's map of the Guadalupes (Jagnow 1979: Fig. 14) shows that most cave passages in our western segment are perpendicular to the shelf margin, which is exactly what we would expect in this highly dissected area. Few remaining passages parallel the canyons because they have been removed by erosion, but remnants persist as surface deposits of cave traver-

sine (*e.g.* Horberg 1949).

We agree with Davis that speleogenesis in the Guadalupes has been episodic and that intensity has varied with time, but do not agree with some of his reasons. Davis wrote, “The watershed has also enlarged with uplift. It follows that the intensity of speleogenesis has varied from east to west as uplift proceeded.” There is evidence that most, if not all, of the uplift of the Guadalupes occurred *prior* to speleogenesis, and that the size of the watershed and recharge area has *decreased* since the onset of hypogenic dissolution (Cunningham *et al.* in prep.). A review of Cenozoic history as it relates to hydrologic conditions in the Guadalupe region illustrates these points.

The Guadalupes are one of many fault block mountain ranges within the Cenozoic Rio Grande rift. The predecessor to the rift, a continental-scale arch extending from Colorado to northern Mexico called the Alvarado Ridge (Eaton 1987), began to rise in Early Tertiary time reaching a maximum elevation of 1500 - 3000 m in southern Colorado. As it rose, material was eroded from highland areas and transported to the flanks, forming a regional erosion surface of Late Eocene age (Epis & Chapin 1975). In the Guadalupes, this erosion surface is preserved in flat upland surfaces distributed throughout the western part of the mountains (Horberg 1949). Renewed uplift in Oligocene and Miocene time tilted the Eocene erosion surface eastward (Horberg 1949) and dissected it by faulting during the opening of the Rio Grande Rift (Eaton 1987). The mountain ranges along the axis of the rift were significantly higher than the tallest peaks of the Guadalupes. For example, Sierra Blanca Peak in the nearby Sacramento Mountains, with an elevation of 3693 m, is about 1000 m higher than Guadalupe Peak.

The water table in the Guadalupes today is approximately at the level of the Pecos River at the town of Carlsbad, New Mexico. In the past, the water table had to be higher, or we would not have large cave systems. Lindsey (1998) concluded that oil fields in southeastern New Mexico and west Texas were water-washed by eastward hydrodynamic flow prior to the opening of the Rio Grande Rift, which required a large, unfaulted upland watershed and stronger hydrodynamic system than exists today.

Hypogenic caves are believed to form by mixing of sulfidic and oxygenated water along steeply curving flow paths within

the Capitan Reef Complex (Davis 1980). Palmer and Palmer (2000) indicate that some cave entrances may have been flowing springs at the time of speleogenesis. Virgin Cave, located in Big Canyon ~5 km from the western escarpment of the Guadalupe, is a hypogenic cave with an entrance elevation of ~2,030 m, ~615 m above the floor of the Salt Basin. To the west, the aquifer had to extend beyond the modern faulted escarpment of the mountains to support upward flow of meteoric water at Virgin Cave. This means that the Salt Basin graben and Border fault zone could not have existed at the time Virgin Cave was formed (DuChene *et al.* 2000; Cunningham *et al.* in prep.).

Major tectonic spasms related to the opening of the Rio Grande rift occurred approximately 17 Ma and 7 - 4 Ma (Eaton 1987). Polyak *et al.* (1998) reported that hypogenic cave-forming events occurred 12.3 - 11.3 Ma, and from 6 - 3.9 Ma. Could it be that the apparent episodic nature of hypogenic speleogenesis is related to quiet periods between tectonic events? The coincidence of the most recent hypogenic cave development (3.9 Ma) and the end of the last tectonic pulse (~4.0 Ma) suggests that downfaulting and erosion were associated with lowering of the water table and may have terminated the most recent phase of hypogenic cave development in the Guadalupe.

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CAVE SCIENCE NEWS

ENCYCLOPEDIA OF CAVE AND KARST SCIENCE PLANNED

Book publishers Fitzroy Dearborn plan to release the *Encyclopedia of Cave and Karst Science*, edited by John Gunn, in December 2002. The Encyclopedia will be a one-volume work of about 1000 large-format pages, and will contain about 350 entries arranged alphabetically. The major topics are archaeology and rock art, biospeleology, conservation and management, history, geosciences and resources, though the largest number of entries will be on world cave and karst sites or regions. The Encyclopedia will also be illustrated with photographs, tables, maps and diagrams, and will have a comprehensive index.

Editor John Gunn is an active caver and cave scientist who is Professor of Geographical & Environmental Sciences and Director of the Limestone Research Group at the University of Huddersfield, UK. He is Joint Editor of the journal *Cave and Karst Science* and Chairman of the International Geographical Union's Karst Commission. Publisher Fitzroy Dearborn, which has offices in Chicago and London, was founded in 1994 to commission and produce high-quality reference books. Previous Fitzroy Dearborn publications, a number of which have gained awards, include the *Encyclopedia of Paleontology* (edited by Ronald Singer, 1999) and the *Encyclopedia of Genetics* (edited by Eric C.R. Reeve, April 2001).

CAVES SYMBOL STYLE NOW INCLUDED IN ARCGIS

A new Caves symbol style, developed from standard symbols in use by caving organizations and the National Park Service, is now included as part of the standard symbols that deliver with ArcGIS, Environmental Systems Research Institute's new Geographic Information System. These symbols have been based on standard symbols in use by the National Speleological Society, Association for Mexican Cave Studies, Proyecto Espeleologia Purificacion, Wind Cave National Park, Hawaii Volcanoes National Park, and Sequoia/Kings Canyon National Park.

The Caves style can be opened by clicking More Symbols in the Symbol Selector dialog, or by opening the Style Manager. To suggest enhancements to the Caves style, or to submit additional symbols, contact Bernie Szukalski at: bszukalski@esri.com.

LIVING WITH KARST - A FRAGILE FOUNDATION Now Available

Living With Karst - A Fragile Foundation is now available. It has been published by the American Geological Institute (AGI) in cooperation with the National Speleological Society, American Cave Conservation Association, Bureau of Land Management, Illinois Basin consortium, National Park Service, USDA Forest Service, U.S. Fish and Wildlife Service,

and the U.S. Geological Survey.

The publication is 4th in the AGI Environmental Awareness Series, and illustrates what karst is and why karst areas are important. The booklet also discusses karst-related environmental and engineering concerns, guidelines for living with karst, and sources of additional information.

The publication is available from AGI at:

<http://www.agiweb.org/pubs/pubdetail.html?item=630601>

The publication is also available from the NSS bookstore: <http://www.caves.org/service/bookstore/>

JOURNAL OF CAVE AND KARST STUDIES SPECIAL GIS ISSUE.

The *Journal of Cave and Karst Studies* is planning a special GIS issue, scheduled for publication in Spring 2002. Submissions are now being solicited, and authors may indicate interest via email to:

Bernie Szukalski, Special Issue Guest Editor:
bszukalski@esri.com

RESEARCH IN NATIONAL PARKS FROM GEOTIMES, APRIL 2001

Recognizing that the parks are a magnificent set of natural laboratories, the National Park Service is working to facilitate scientific research in parks. The Park Service welcomes proposals for studies designed to increase our understanding of the human and ecological processes and resources in parks, as well as proposals that seek to use the unique values of parks to develop scientific understanding for public benefit.

A scientific research and collecting permit is required for most scientific activities pertaining to natural resources in National Park System areas that involve field work and specimen collection or that have the potential to disturb resources or visitors.

Recently, the Park Service initiated an automated research permitting and reporting system, accessible at science.nature.nps.gov/research. The site, still under development, will make it easier for potential investigators to apply for permits to conduct field work within units of the National Park System, review permit requirements and restrictions, review the objectives and findings of previous studies, easily provide annual accomplishment reports, and to search and review the research activities park managers are most interested in attracting.

The time and effort required to review the permit application and accompanying study proposal will be proportional to the type and magnitude of the proposed research. For example, a single visit for a non-manipulative research project will often require a relatively simple proposal and the permitting decision should be relatively fast. A highly manipulative or intrusive investigation, however, with the potential to affect nonrenew-

able, rare, or delicate resources, needing detailed planning or logistics, would receive more extensive review. Park managers will work with applicants to arrive at a mutually acceptable research design. However, there may be activities where no acceptable mitigating measures are possible and the application may be denied. The Web site provides additional information on the factors that influence permitting decisions.

Applications for permits must include a research proposal and should normally be submitted at least 90 days in advance of planned field activities. Each proposal will be reviewed for compliance with National Environmental Policy Act requirements and other laws, regulations and policies. The park superintendent may also require internal or external scientific review, depending on the complexity and sensitivity of the work being proposed and other factors.

Applicants can expedite the review by providing photocopies of existing peer reviews, or by providing names, mailing addresses and e-mail addresses of people who could review a proposal.

Researchers working in parks are required to complete an NPS Investigators Annual Report form for each year of the permit, including the final year. These reports are used to document accomplishments of research conducted in parks. Park research coordinators may request copies of field notes, data, reports, publications or other materials resulting from studies conducted in parks.

Individuals may obtain materials via the Internet or by contacting the park in which the work will be conducted. Visit www.nps.gov for individual park addresses.

All application materials must be submitted to the park in which you plan to work, via Internet or mail.

ANDREA HUNTER RECEIVES EXPLORATION SCHOLARSHIP

The Rocky Mountain Chapter of The Explorers Club has presented an Exploration Scholarship to Andrea Hunter. Ms. Hunter's research project is titled "Environmental Disturbance of Bacteria and Effects on Water Quality in a Karstic Setting." Her work will address some critical issues regarding the protection and preservation of cave ecosystems and she will be working in Carlsbad Cavern National Park. Hunter is a student at the University of New Mexico in Albuquerque.

The Exploration Scholarship program of the Rocky Mountain Chapter of The Explorers Club provides small grants to assist students with their field research. Applications for these scholarships should include a one-page description of the proposed field research, a curriculum vita, and a letter of reference from the applicant's advisor. Send application materials to: Dr. James Pisarowicz; Exploration Scholarship Chairperson; Wind Cave National Park; RR 1 Box 190; Hot Springs, SD 57747.